

# Physics potential of beta-beams

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Beta-beams is a novel concept for the production of neutrino beams exploiting boosted radioactive ions which decay through beta-decay. Here we describe a project, currently under investigation, where such beams are used to address the issue of CP violation in the lepton sector. We also mention the interest of having low-energy beta-beams. The connection to projects for the production of very intense exotic ion beams, like EURISOL, is emphasized.

## 1. Introduction

Nuclei represent a precious laboratory for the study of fundamental issues like neutrino properties. Pauli first postulated the existence of these elusive particles to explain the missing energy observed in nuclear beta decay. A very timely example is offered by the present search for the absolute value of the neutrino mass through tritium beta-decay. The important issue of the Dirac or Majorana nature of neutrinos is addressed by experiments that look for neutrinoless double-beta decay in nuclei [1].

Neutrino oscillation experiments have shown nowadays that neutrinos are massive particles. This phenomenon depends on the so-called neutrino mixing angles and on the difference between the square of the masses. These experimental observations are accounted for by introducing the Maki-Nakagawa-Sakata-Pontecorvo (MNSP) matrix which relates the neutrino flavor to the mass basis, like the Cabibbo-Kobayashi-Maskawa (CKM) matrix in the quark sector. This unitary matrix depends on the three mixing angles and one (Dirac) phase introducing CP violation in the lepton sector. In order to measure CP violating effects, one needs to perform comparative studies of neutrino versus anti-neutrino oscillations like, e.g. comparing  $\nu_e \rightarrow \nu_\mu$  with  $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ . Several other important issues are still open on neutrino properties, among which their Dirac versus Majorana nature, the electromagnetic properties or the absolute mass scale [1].

Various methods to produce intense neutrino beams are now explored, based on intense conventional (from the decay of pions and muons) beams - also called super-beams - or on new concepts, like neutrino factories [1]. In this respect, nuclei can offer a precious tool through the novel concept of beta-beams: pure (anti-)electron neutrino beams produced by accelerating radioactive ions that decay through beta-decay [2].

## 2. The Beta-beam Project

Beta-beams have been the starting point for a new project at CERN, at present under investigation. According to the first feasibility study [2,3], the neutrino beams are obtained by producing, collecting and accelerating the ions, first at several hundred MeV and then to GeV energies, by injection in the (already existing) PS and SPS. At present, the best candidates as  $\bar{\nu}_e$  ( $\nu_e$ ) emitters are  ${}^6\text{He}$  ( ${}^{18}\text{Ne}$ ). The (anti-)neutrino energies are tuned to meet the neutrino oscillation frequencies (note that the ion Lorentz gamma factor is related to the neutrino energy according to  $E_\nu = 2\gamma Q_\beta$  with  $Q_\beta$  being the beta Q-value). Once the ions have reached the required energies, they are injected in a storage ring with long straight sections (2.5 km for a total length of 7 km). Such a ring needs to be built [2,3]. All the ions (about  $2 \cdot 10^{14}$   ${}^6\text{He}$  and  $10^{13}$   ${}^{18}\text{Ne}$ ) along the straight sections produce neutrino beams that are fired to far detectors for the comparative study of  $\nu_e \rightarrow \nu_\mu$  and  $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$  oscillations. The production and first acceleration steps present strong links to the european EURISOL conceptual design. This has resulted in a common bid for a design study withing the 6th European Union Framework program.

Various scenarios to perform CP violation studies are being proposed [2,3,4,5,6,7]. In the first scenario [2,3,4,7], beta-beams are fired to a Cherenkov detector like UNO [8] (440 ktons fiducial volume, 20 times bigger than the present Super-Kamiokande detector), located in an (upgraded) Fréjus Underground Laboratory, 130 km from CERN. To match this distance, the ions have to reach a Lorentz factor  $\gamma=100$  (60) for  ${}^{18}\text{Ne}$  ( ${}^6\text{He}$ ). Note that the gigantic detector can be used to improve the present sensitivity on proton decay and as a core-collapse supernova neutrino observatory. Other interesting scenarios have been proposed where the ions are accelerated to much higher energies and sent to further distancies, like e.g. to the Gran Sasso laboratory [5,6]. The feasibility of the very high-gamma scenarios needs further studies. Figure 1 shows the CP sensitivity that can be achieved in the different scenarios, as a function of the neutrino mixing angle  $\theta_{13}$  [5]. Finally, this project has the attractive feature that if conventional beta-beams (producing both  $\nu_\mu$  and  $\bar{\nu}_\mu$ ) are sent to the same detector, T and CPT violation studies can also be addressed by comparing  $\nu_e \rightarrow \nu_\mu$  with  $\nu_\mu \rightarrow \nu_e$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations respectively [4].

## 3. Low-energy Beta-beams

The beta-beam concept can also be used to establish a facility producing neutrinos with low energies (i.e. several tens of MeV up to a hundred) [9]. Such a facility can be either part of the high energy facility at CERN, or part of one of the laboratories producing intense radioactive ion beams in the future [9]. The option of a low-energy neutrino facility based on conventional beams is also at present under study [10]. In [11] a detailed comparison between the two options for the study of neutrino interactions on lead is presented.

The availability of low energy neutrino beams would offer the opportunity to address a rich physics program [9,10,12]. In [13] the potential of low-energy beta-beams is explored as far as the neutrino magnetic moment is concerned. In this case the ions are produced, collected and used as an intense neutrino source at rest, inside a  $4\pi$  detector. It is shown that one might improve present upper limits, obtained with direct measurements, by almost an order of magnitude. Sistematic studies on neutrino-nucleus interactions can

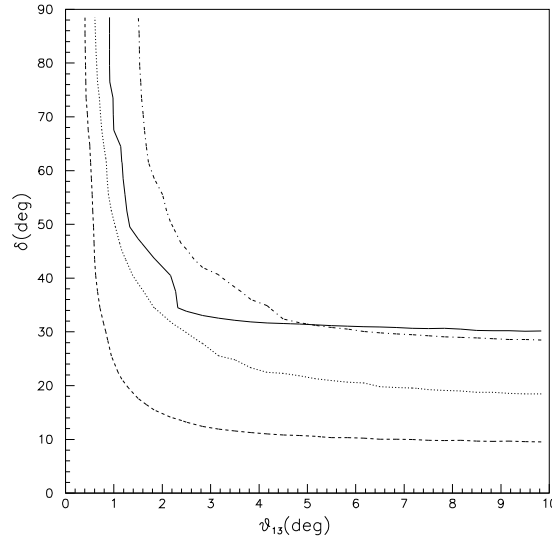


Figure 1. CP sensitivity -defined as the ability to discriminate between  $\delta = 0^\circ$  and  $180^\circ$  with 99% C.L.- for the following different scenarios: CERN to Fréjus, with  $\gamma=100$  (60) for  $^{18}\text{Ne}$  ( $^6\text{He}$ ) and a UNO-type detector (solid line); CERN to Gran Sasso, with  $\gamma=580$  (350) for  $^{18}\text{Ne}$  ( $^6\text{He}$ ) and UNO (dashed line) or a factor 10 smaller (dashed-dotted line); CERN to Canary islands, with  $\gamma=2500$  (1500) for  $^{18}\text{Ne}$  ( $^6\text{He}$ ) and a 40 kton detector [5].

also be performed e.g. by putting a close detector to the storage ring where low-energy beta-beams are collected [14]. This is a topic of current great interest for various domains of physics [12,15,16]. Table I shows neutrino-nucleus interaction rates expected for  $\gamma=14$  and a small or a large storage rings. The former corresponds to the one planned for the future GSI facility while the latter is the ring included in the beta-beam baseline scenario at CERN (Details can be found in [14]). An advantage of beta-beams is that one can vary the average neutrino energy by accelerating the ions to different gammas. From Table I one can see that interesting neutrino-nucleus interaction rates can be obtained by using typical parameters available from existing feasibility studies. Therefore, low-energy beta-beams could offer a unique opportunity to perform neutrino-nucleus studies of interest for nuclear physics, particle physics and astrophysics [9,14].

In conclusion, these projects are very promising. A detailed feasibility study will be performed, jointly with the EURISOL design study, in the coming years.

## REFERENCES

1. See the Proceedings to “Neutrino 2004”, 14-19 juin 2004, Paris.
2. P. Zucchelli, Phys. Lett. B 532 (2002) 166.
3. B. Autin et al, J. Phys. G 29 (2003) 1785 [physics/0306106]; M. Lindroos,

Table 1

| Reaction                      | Ref. | Mass<br>(tons) | Small Ring<br>( $L=450$ m, $D=150$ m) | Large Ring<br>( $L=7$ km, $D=2.5$ km) |
|-------------------------------|------|----------------|---------------------------------------|---------------------------------------|
| $\nu + D$                     | [15] | 35             | 2363                                  | 180                                   |
| $\bar{\nu} + D$               | [15] | 35             | 25779                                 | 1956                                  |
| $\nu + {}^{16}\text{O}$       | [17] | 952            | 6054                                  | 734                                   |
| $\bar{\nu} + {}^{16}\text{O}$ | [17] | 952            | 82645                                 | 9453                                  |
| $\nu + {}^{56}\text{Fe}$      | [18] | 250            | 20768                                 | 1611                                  |
| $\nu + {}^{208}\text{Pb}$     | [19] | 360            | 103707                                | 7922                                  |

Neutrino rates (events/year) on deuteron, oxygen, iron and lead [14], with  $\gamma = 14$  for the parent ion. The cross sections are taken from referred references. The detectors are located at 10 meters from the storage ring and have cylindrical shapes ( $R=1.5$  m and  $h=4.5$  m for deuteron, iron and lead,  $R=4.5$  m and  $h=15$  m for oxygen, where  $R$  is the radius and  $h$  is the depth of the detector). Their mass is indicated in the second column. Rates obtained for two different storage ring sizes are presented ( $L$  is the total length and  $D$  is the length of the straight sections). Here  $1 \text{ year} = 3.2 \times 10^7 \text{ s}$ .

- physics/0312042. See also <http://beta-beam.web.cern.ch/beta-beam/>.
4. M. Mezzetto, J. Phys. G 29 (2003) 1771 [hep-ex/0302007]; J. Bouchez, M. Lindroos, M. Mezzetto, Proceedings to “Nufact03” [hep-ex/0310059].
  5. J. Burguet-Castell et al, Nucl. Phys. B 695 (2004) 217 [hep-ph/0312068].
  6. F. Terranova et al., hep-ph/0405081.
  7. A. Donini et al, hep-ph/0406132.
  8. C.K. Jung, Proceedings of the “Next generation Nucleon Decay and Neutrino Detector (NNN99)” Workshop, September 23-25, 1999, Stony Brook, New York9.
  9. C. Volpe, Jour. Phys. G 30 (2004) L1 [hep-ph/0303222].
  10. F.T. Avignone *et al.*, Phys. Atom. Nucl.63 (2000) 1007; see <http://www.phy.ornl.gov/orland/>; Y. Efremenko, private communication.
  11. G.C. McLaughlin, nucl-th/0404002.
  12. See also J. of Phys. G 29 (2003) 2497; A.B. Balantekin and G.M. Fuller, J. Phys. G 29 (2003) 2513 [astro-ph/0309519]; A.B. Balantekin, Prog. Theor. Phys. Suppl. 146 (2003) 227 [nucl-th/0201037]; K. Langanke and G. Martinez-Pinedo, Nucl. Phys. A 731 (2004) 365.
  13. G.C. McLaughlin and C. Volpe, Phys. Lett. B 591 (2004) 229 [hep-ph/0312156].
  14. J. Serreau and C. Volpe, to appear in Physical Review C [hep-ph/0403293].
  15. K. Kubodera and S. Nozawa, Int. J. Mod. Phys. E 3 (1994) 101 and references therein.
  16. C. Volpe, Proceedings to “Neutrino 2004”, 14-19 juin 2004, Paris [hep-ph/0409249].
  17. E. Kolbe, K. Langanke, P. Vogel, Phys. Rev. D 66 (2002) 013007; W.C. Haxton, Phys. Rev. D 36 (1987) 2283.
  18. E. Kolbe and K. Langanke, Phys. Rev. C 63 (2001) 025802.
  19. C. Volpe et al, Phys. Rev. C 65 (2002) 044603.